Optimization of seam annealing process with the help of 2D simulations

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Introduction

In the production of welded pipes according to API standards, a normalization of the weld and heat affected zone (HAZ) is required. The weld of thick-walled tubes shows an hour-glass shaped HAZ caused by the ”corner effect” in the weld Vee. The microstructure, particularly at the external and internal surfaces, is very coarse-grained. The aim for the heat treatment is to reestablish a homogeneous and fine-grained microstructure in the HAZ.

To achieve a fine-grained microstructure after the normalization, it is important to limit the temperature on the external surface of the pipe, which is closest to the coil, to avoid grain re-growth, and to reach high enough austenitisation temperature in a sufficiently wide zone at the inner surface. The width at the inner surface must cover the width of the HAZ, which has its maximums at the surfaces, and the positioning tolerance of the heat zone to the weld.

Even if low frequency is used for the reheating of the weld zone, the heat penetration through the pipe wall is partly reliant on heat conduction. Time needed for temperature equalization through heat conduction increases proportionally to the square of the wall thickness. The preferred welding method is by induction, which requires higher minimum welding speed (minimum 10 – 12 m/min) than contact welding (minimum 5 – 6 m/min). One complication with in-line normalizing heat treatment of thick-walled pipes is that the heating requires considerable length in a line. This is due to the time needed for temperature equalization through the pipe wall and the required line speed. An important design work is to optimize the temperature distribution in the heat zone and establish the minimum heating length required. A 2D simulation, using coupled electromagnetic and transient thermal calculations in a cross-section of the weld as it passes through the different heating zones, is today an indispensable tool. It is important to have good representations of the very nonlinear and temperature dependant electrical and physical properties of the steel, as well as heat losses by convection and radiation from the surfaces and residual heat from the welding.

The maximum temperature limit as well as the required minimum austenitisation temperature is dependent on actual steel quality and required microstructure. The time at maximum temperature for the surface close to the coil is from a few seconds up to a few tens of seconds. Steel used in pipes that are produced according to API standards normally contains alloy elements that resist or slow down grain growth. One such element is aluminum, in the form of fine aluminum nitride particles, that remain un-dissolved up to a certain temperature. Above this temperature, often referred to as grain coarsening temperature, the speed of grain growth increases rapidly. Other alloy elements that slow down grain growth are vanadium, titanium and niobium [1]. In our calculations we have used 1100ºC as maximum temperature and 900ºC as required minimum austenitisation temperature.

In a production line the external surface is accessible for temperature measurements, but the internal temperature can only be judged through metallurgical examination of the obtained microstructure (off-line check). The simulation results, therefore, are also helpful in gaining a view of the temperature distribution through the pipe wall and taking the right measures in case of unacceptable results. Normally in a line, the surface temperature in the center of the heated zone is used to regulate the power to prevent overheating of the steel.

Normalization is defined as heating to austenitisation temperature and cooling in still air. This is not the case for seam normalizing as the colder part of the pipe acts as a heat-sink and the temperature slope after heating is, first of all, a result of the internal heat conduction in the pipe. The rather fast cooling obtained, however, can be beneficial in producing a fine-grained microstructure. To limit the length of the line one wants to start the final water-cooling as early as possible. It is, however, important that the transformation of the austenite be finalized. If the austenite is retained at the point of water cooling, it results in quenched microstructure as martensite. This normally is not allowed, at least not as un-tempered martensite. The ITT (Iso-Temperature-Transformation) and CCT (Constant-Cooling-Transformation) diagrams of the materials in question and the calculated cooling curve are helpful tools in designing the cooling part of the process.

The Model

We have represented the process by a 2D cross-section of the tube and coil. In the real process the tube moves through the production line and passes underneath a row of seam annealing coils. By turning the power on and off it is possible to simulate this movement. In order to reduce the number of computations in sequence, we have left out the space between the coils in the study on coil design. We have, therefore, computed on 3 equivalent sections and the final cooling after the seam annealing section. The symmetry of the geometry allows us to model only half the problem. We have used the software Flux 2D. The layout of the model with a classical seam annealing coil is shown in figure 1.

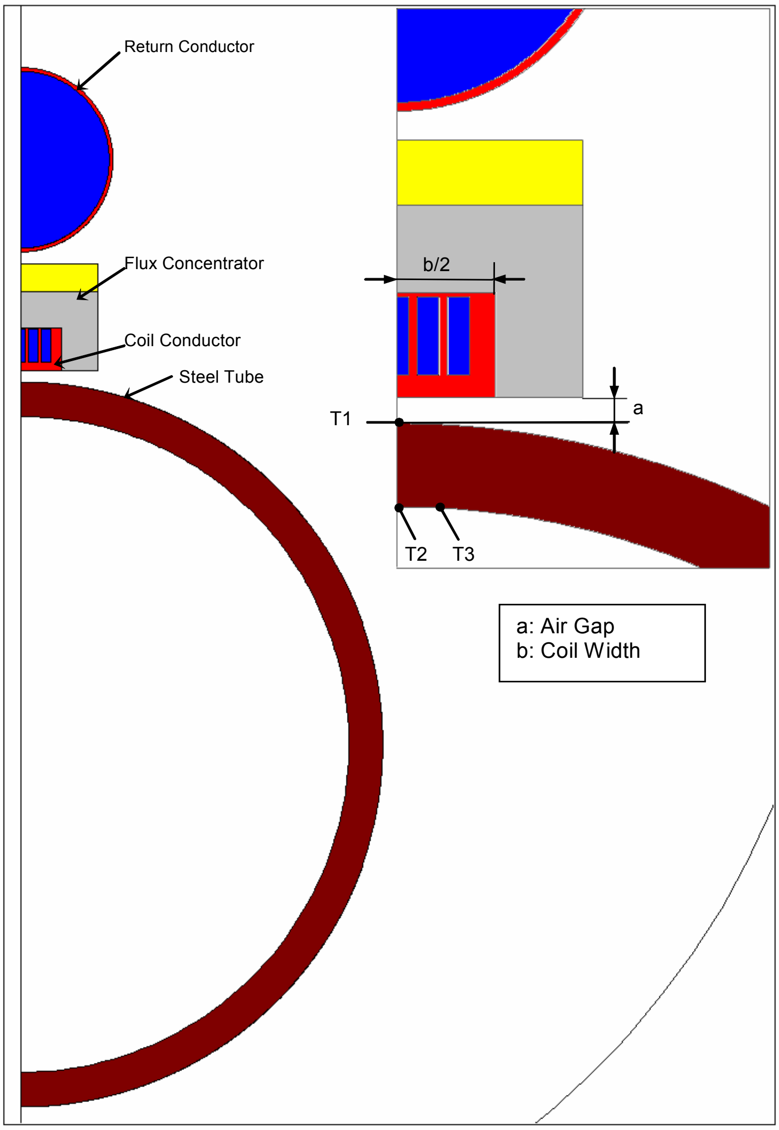

Figure 1. Computation domain

In the computations only the tube itself and the surface regions that enable heat exchange from the tube to the surroundings are included in the thermal part of the problem. For the regions not included in the thermal part, the representations of the material properties are simpler. Except for the magnetic properties of the coil core, they are all constant. The property assigned to the tube is the same throughout the computations, but properties for the tube surface can be changed to represent different cooling conditions.

When the tube arrives at the first annealing coil, there is a temperature distribution in the tube wall from the welding process that depends on the speed of the line, the distance from welder to the first annealing and often water cooling applied to allow ultrasonic inspection of the weld. The high temperatures from the welding process are limited to a rather small mass and even out quite fast [2]. Just as important is the heat generated in the tube by the current going around the tube underneath the induction welding coil. In the calculations on coil design presented in this paper, we have started the computations with an elevated temperature of 200 °C in the entire tube. This temperature is calculated on the basis of data we have from welders in mills running similar sized tubes.

In the presentation of the results, we have used three reference points for temperature measurement. These can be seen in figure 1. Temperatures T1 and T2 are at the symmetry line in the centre of the tube, T1 on the outer surface and T2 on the inner surface. The point for temperature measurement T3 is on the inner surface 10 mm from the symmetry axis.

Measurements

To verify that our computations are reliable, we have taken some measurements with our profiled coil. In this test we split one tube along its length to get two half pipes. This made the inner surface of the tube more accessible for temperature measurements. A setup like this is slightly different from an actual mill. Computations, therefore, have been done on the same “half pipe” setup. We have used material property data for steel 35CD4 (35CrMo4, AISI 4135) because good data is available for this particular steel and the steel used in the tests, FeE 255, has properties close to 35CD4.

There were several factors influencing the accuracy of the measurements in this test. Due to the thermal expansion in the heated zone, the tube will bend when it is heated. Since we used halves of a tube, the tube’s rigidity was severely weakened. This allowed the tube to bend much more than it would in an actual mill and resulted in some movement of the tube during heating and, therefore, inaccuracy in the position of the thermocouples. Temperature measurements were taken on a cross-section at the middle point of the coil. When the tube was heated, we allowed it to bend away from the coil at the ends. At the same time we placed insulating material between coil and tube at the mid point to ensure that the distance between the two remained acceptably constant at this point.

Temperatures are measured with thermocouples, type K, welded on the inner and outer surface at distances from the centerline of the tube’s heated zone. The three points representing the temperatures from the computations (T1 – T3) are presented in figure 2.

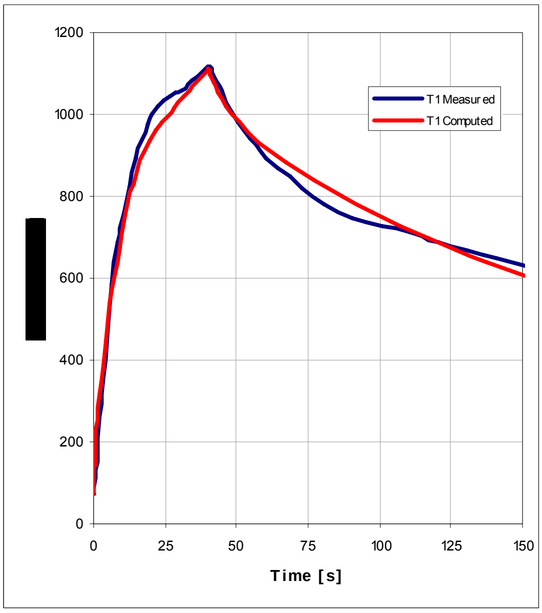

Figure 2a. T1

The tube had a temperature of 75 °C at power on. The computation for direct comparison with the measurements was started at the same temperature.

When we compare calculated and measured temperatures, we see that the measured values are generally a few degrees higher. This can be explained as inaccuracy in current measurement or air gap.

Data:
OD Tube: 327 mm
Wall Thickness: 17 mm
Air Gap: 6 mm
Coil Current: 9700 A
Frequency: 1450 Hz

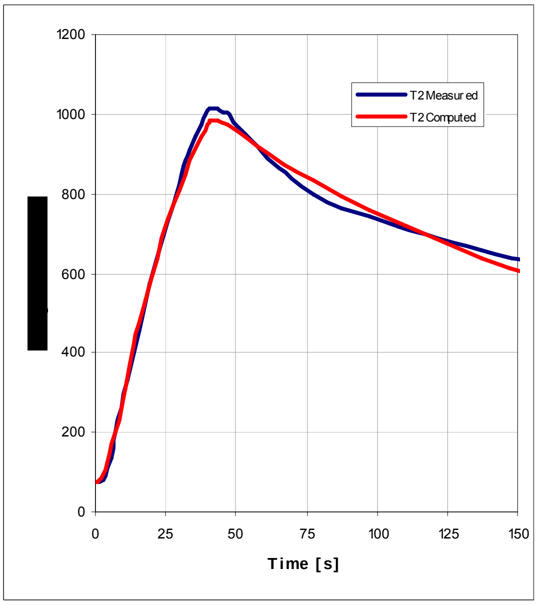

Figure 2b. T2

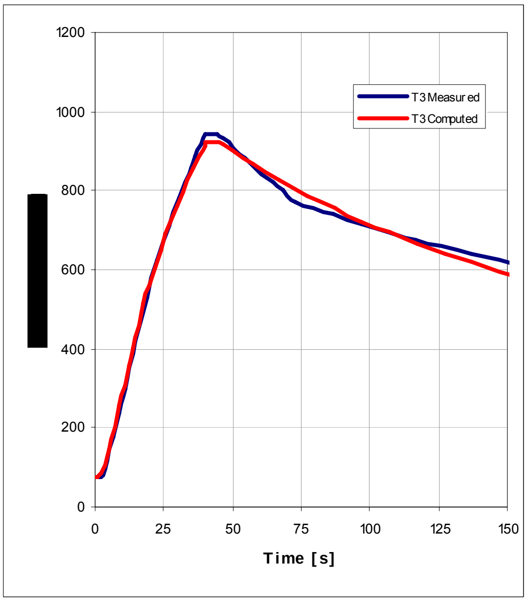

Figure 2c. T3

The specific heat value v.s. temperature have during heating a hunch around 730 – 800 °C due to the energy required to transform the material to austenite. In our calculation, the same specific heat value v.s. temperature is used during cooling. In reality the transformation energy is released at lower temperatures as the transformation from austenite takes place at lower and cooling-rate-dependant temperatures. This simplification in representation of material properties is visible in the curves during cooling. For our purposes, we can conclude that there is good conformity since we are looking at cooling until transformation is completed. At this point, all the transformation energy is released.

Coil design

When the coil is narrow compared with the wall thickness, the heated zone has a shape that resembles a half-cylinder. The heatflow lines, that are perpendicular to the iso-temperature lines, bends tangential close to the inner surface. A narrow coil, therefore, requires longer heating time (zone length) than a wider coil, where the heatflow has a more radial direction in the required zone width at the inner surface.

Table 1: Temperature scale for T-color shade plots

🟦	160 – 220	🟪	400 – 460	🟧	640 – 700	🟨	880 – 940
🟦	220 – 280	🟪	460 – 520	🟧	700 – 760	🟨	940 – 1000
🟦	280 – 340	🟥	520 – 580	🟧	760 – 820	🟨	1000 – 1060
🟦	340 – 400	🟥	580 – 640	🟧	820 – 880	🟨	1060 – 1120

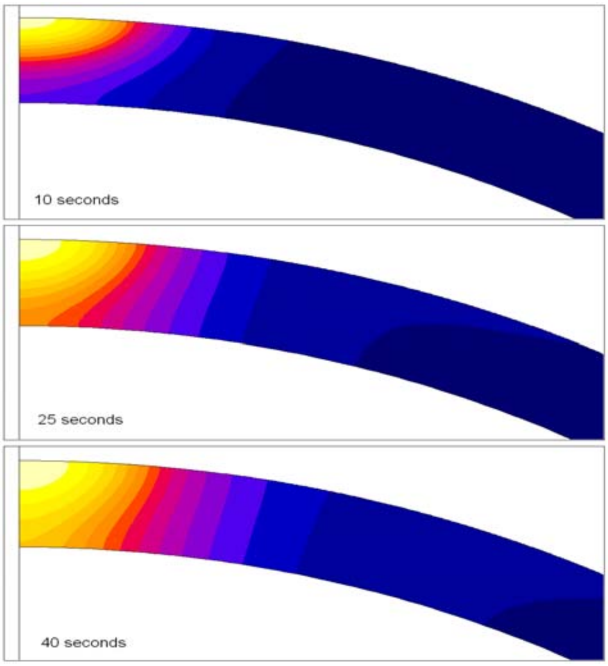

Figure 3a. T-colour shade plots For 45 mm classic coil

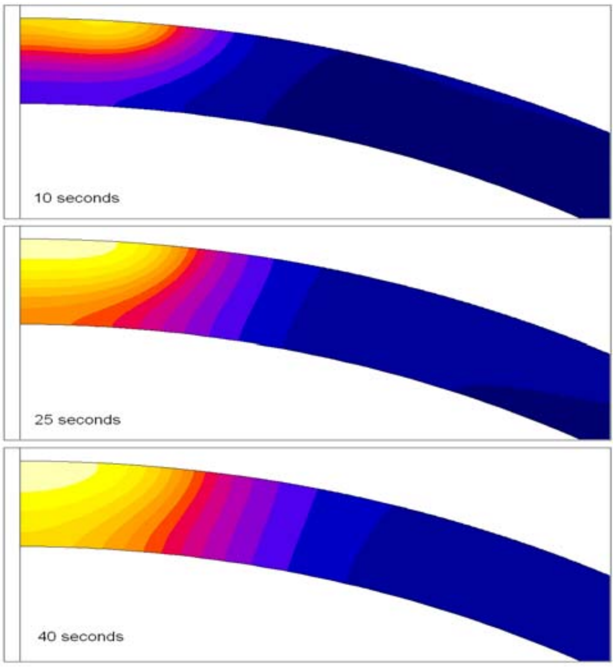

Figure 3b. T-colour shade plots For 60 mm EFD Profiled Coil

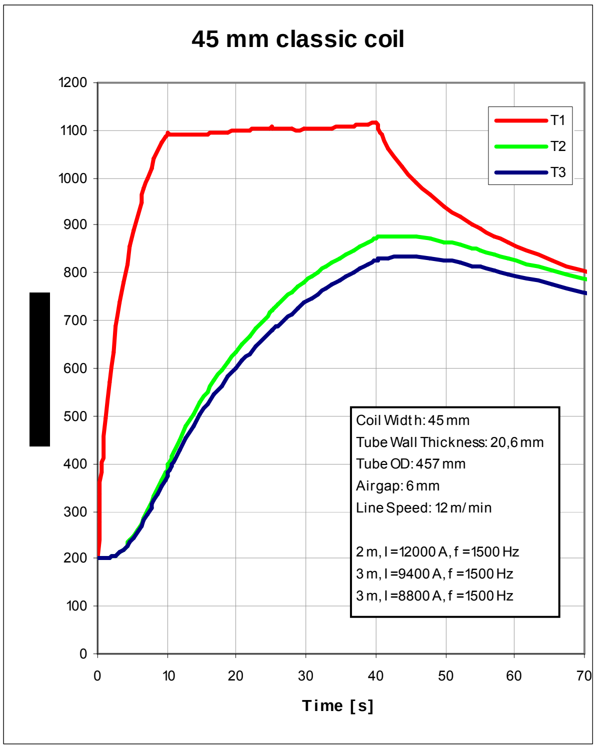

Figure 4a. Temperature vs. time plots

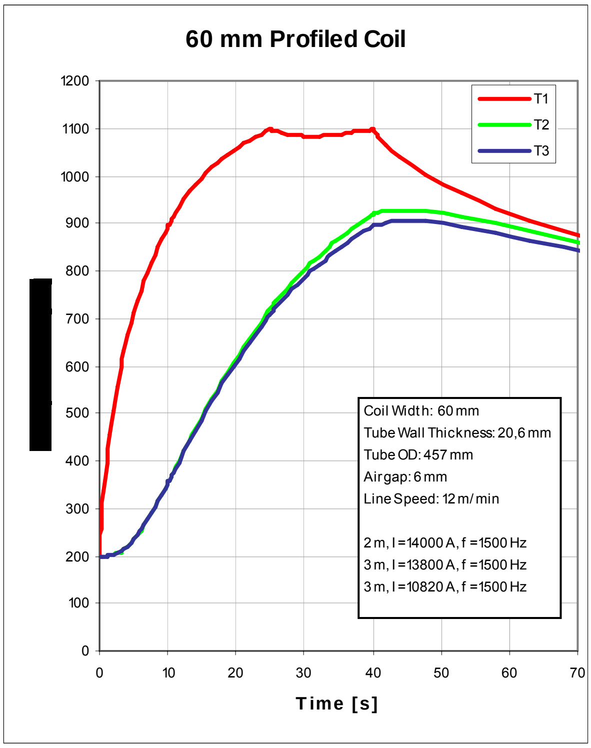

Figure 4b. Temperature vs. time plots for 60 mm EFD profiled coil

for 45 mm classic coil

When the material passes Curie-temperature, a non-magnetic ”channel” is formed by the amount of material that has exceeded the Curie-temperature. The shape of this ”channel”, or zone, determines the current distribution during the time when this ”channel” is expanding. It is possible to optimize the heated zone by adapting the coil profile and coil width.

With an increase in the coil width from 45 mm to 60 mm on wall-thickness 20,6 mm, the required power increases about 14%. The increase in power is less than the increase in coil width because, for the wider coil, the zone length can be shorter resulting in a shorter heating time. With longer heating time, the zone width is widened due to heat conduction into the pipe.

Normally one type of coil must cover a range of wall thicknesses. Coils with sufficient width to heat the largest wall thickness at minimized heating zone length create a wider zone and require more power than necessary for the smaller wall thickness range. A wider heated zone gives better temperature homogeneity, which may also lower the maximum temperature for smaller wall thicknesses. The zone width also influences the temperature curve’s slope during cooling down after the heating.

Frequency

We have made a comparison where the two first heating zones of 2 m and 3 m are run at equal conditions in both cases at a frequency of 1,5 kHz. In the first case the third zone has a frequency of 1,5 kHz and in the second case 0,75 kHz. We see that the temperature difference $\Delta T = T1 - T3$ drops from 193 °C in the first case to 169 °C in the second case. The conclusion is as expected, a lower frequency improves the temperature homogeneity. A lower frequency, therefore, makes it possible to get more power into the tube without exceeding the maximum temperature at the surface. Another aspect of lowering the frequency is that the coil impedance will be lower.

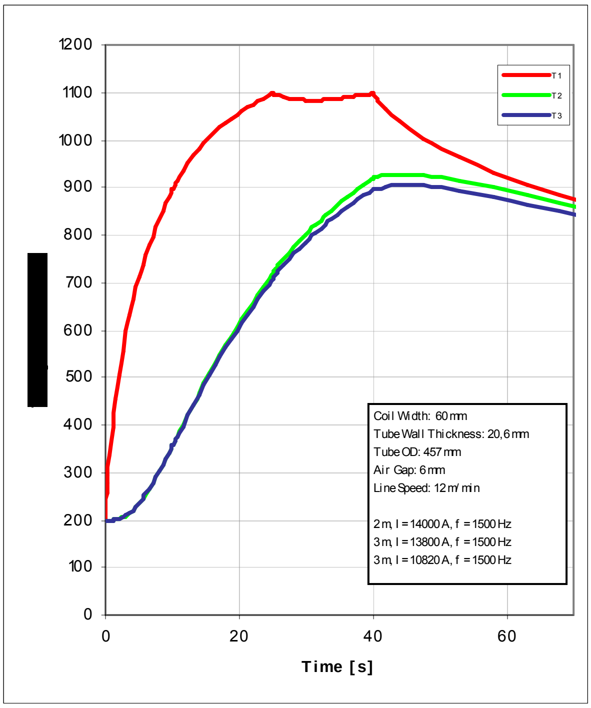

*Figure. 6a. 3*1500 Hz*

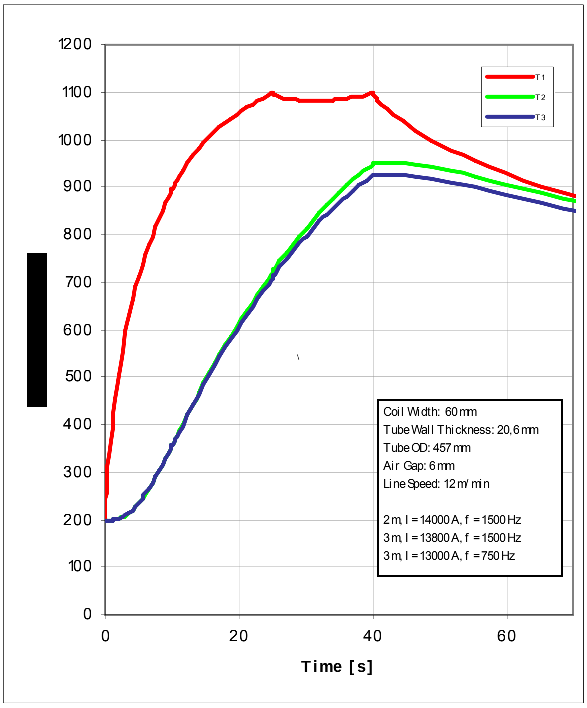

*Figure 6b. 2*1500 Hz +1*750 Hz*

Conclusions

Comparison of the measurements and calculated results by using Flux2D shows good conformity. However, we see that our model, using the same values for specific heat during heating and cooling, gives small errors in a certain temperature range during cooling.

Shortening the heating zone to a minimum requires optimization of coil width and profile with respect to wall thickness and speed. However, optimization of a coil for the most critical wall thickness may have the consequence that the required power increases for smaller wall thicknesses due to a zone that is wider than necessary. A wider zone improves temperature homogeneity and influences on the cooling slope in the natural cooling zone.

A lower frequency in the last section improves temperature homogeneity in the tube. In the frequency range used for this application, acoustic noise is a problem that has to be addressed.

A 2D simulation applying coupled electromagnetic and transient thermal calculations is a very capable and necessary tool for optimization of the heating and cooling zones of a seam annealing line.

References:

[1.] Georg Krauss. Steels: Heat Treatment and Processing Principles, ASM International 1989.

[2.] Bjørnar Grande, John Inge Asperheim. Factors Influencing Heavy Wall Tube Welding. Tube and Pipe Technology March/April 2003.